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Carrier-envelope phase-dependent electron tunneling in a coupled double-quantum-dot system driven by a few-cycle laser pulse

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ABSTRACT

We theoretically investigate the dependence of the electron tunneling on the carrier-envelope phase of a few-cycle laser pulse in a coupled double-quantum-dot system, and we show that the electron tunneling between coupled quantum dots is very sensitive to the carrier-envelope phase under a change of the parameters of the system. This in turn provides an additional means to measure the carrier-envelope phase of a laser pulse at lower laser intensity regime in the solid-state nanostructure.

1. Introduction

The carrier-envelope phase (CEP) of ultrashort few-cycle laser pulses [1] plays a crucial role in strong-field dissociation [2,3], strong-field ionizations [4,5], attosecond electron dynamics [6–8], and high-harmonic generation [9], etc. The CEP may be determined by measuring a spatial asymmetry in ionization [6,10], soft-X-ray radiations [11], XUV radiations [12], and electron emission from metal surfaces [13].

The previous investigates on the CEP-dependent effects have concentrated mainly on the ionization, the photoemission, and the coherent and de-coherent behaviors of ionization yields in the tunneling ionization regime. Recently, it has found the sensitive CEP dependence in bound-state dynamics at weak field rather than ionization or photoelectron yields in the multiphoton ionization regime, where the tunneling ionization hardly takes place. For instance, Wu and Yang [14] have pointed out that the CEP of few-cycle laser pulses has a profound influence on the bound-state atomic coherence even in the weak-field regime (the corresponding Rabi frequency is much less than the involved transition frequency) and have studied the CEP-dependent quantum beats and its measurement by using a three-level atomic model.

On the other hand, it has been noted that quantum dots (QDs) and coupled quantum dots (CQDs), which are respectively referred to as "artificial atoms" and "artificial molecules", provide a highly tunable quantum system and have attracted great attention due to their potential applications in the development of novel optoelectronic devices and solid-state quantum information science. Different from real atoms and molecules, the quantum properties of these nanostructures can be well manipulated by accurately tailoring their shapes and sizes or by applying external fields [15–18]. Several successfully performed experiments have aided the theoretical predictions [19–29]. For practical applications, the idea of connecting the ultrafast world of few-cycle lasers with the ultrasmall world of nanosize systems like QDs/CQDs with tailored properties is very promising. To use such a combination for measuring the CEP therefore seems to be a very logical step.

In this Letter, we present a systematic theoretical study for the electron tunneling response of a coupled double-quantum-dot system under a change of the CEP by a few-cycle laser pulse. We show that the tunneling of the electrons between the CQDs is extremely sensitive to the CEP for different values of the duration (τ) of the few-cycle laser pulse, the amplitude (Ω_L) of the few-cycle laser pulse, the detuning (ω_{12}) and the strength (T_e) of the

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voltage-controlled tunneling, also providing a route to a new measurement technique of the CEP.

The major advantages of applying our considered CQD scheme over other methods are as follows. Firstly, the CQD medium studied is a solid, which is much more practical than that in gaseous medium due to its flexible design and the wide adjustable parameters. The CQD medium here provides a highly tunable quantum system. The quantum properties of these nanostructures such as the transition energies and dipole moments can be well manipulated by accurately tailoring their shapes and sizes while they can hardly be found in the models for cold atom media [30]. Secondly, it should be pointed out that tunneling control by bias voltage is a phenomenon exploited in devices such as resonant tunneling diodes. But here, it is used for an efficient and convenient manipulation of the CEP-dependent electron population. Previous investigations on the CEP dependence in gaseous medium are usually based on the bound-state atomic coherence and therefore are substantially different from our proposed scheme. What is more important, the CEP dependence of the electron tunneling revealed here is considerably greater than the CEP dependence of the bound-state atomic coherence and the quantum beats studied previously [14].

The outline of this Letter is arranged as follows. In the following section we establish the theoretical model under study and derive the dynamical equations of motion. In Section 3, we analyze the CEP-dependent population in the right dot describing the electron tunneling of the CQDs via numerical simulations and further present the corresponding physical explanations. We also briefly demonstrate its phase detection. In Section 4, we conclude with a brief summary.

2. Model and equations of motion

Consider a lateral CQD nanostructure consisting of two dots (the left dot (LD) and the right dot (RD)) with different band components coupled by tunneling as sketched in Fig. 1. At nanoscale interdot separation the hole states are localized in the QDs and the electron states are rather delocalized. With the application of a few-cycle laser pulse, an electron is excited from the valence band to the conduction band of one of the QDs. This electron can be transferred by tunneling to the other QD. Fig. 1(a) presents a schematic of the system. The tunnel barrier in a double QD can be controlled by placing a gate electrode between the two QDs. In the absence of the gate voltage the conduction-band electron energy levels are out of resonance and the electron tunneling between two dots is very weak. In the presence of a gate voltage the conduction-band electron levels come close to resonance and the electron tunneling between the two QDs is significantly enhanced. In addition, in the latter case the valence-band energy levels become more off-resonant and therefore the hole tunneling can be neglected. Figs. 1(b) and 1(c) describe band structure and energy-level diagram of the lateral CQDs. The interaction of the CQD structure with the applied few-cycle laser pulse can be described by three states: the ground state $|0\rangle$, where the system has no excitations, the direct exciton state $|1\rangle$, where a pair of an electron and a hole are bound in the LD, and the indirect exciton state $|2\rangle$, where the hole is in the LD and the electron is in the RD. For more details on this system, we refer the reader to Refs. [31–33] and references therein.

For a few-cycle laser pulse, the electric field is expressed as $E(t) = E_0 f(t)\cos(\omega_L t + \varphi_L)$ where $f(t)$ is the field envelope, E_0 is the peak of the field envelope, ω_L is the carrier frequency ($T_0 = \frac{2\pi}{\omega_L}$ is an optical oscillation cycle time), and φ_L is the CEP. The CEP describes the offset of the peak laser field relative to the peak position of the envelope. Here, we assume that the temporal intensity profile is Gaussian with pulse duration τ [full width at half maximum (FWHM)], i.e., $f(t) = e^{-(2\ln 2)t^2/\tau^2}$. Examples of such pulses are shown in Figs. 2(a)–(c). It is evident that the electric field as a function of time depends on the CEP, although the envelope is the same for all pulses. As can be seen in the figure, a phase shift $\Delta\varphi_L$ of $\pi/2$ changes the peak value of the central oscillation near the envelope maximum considerably. All physical processes induced by this field will depend on this CEP. In the few-cycle regime, in addition to the pulse envelope $f(t)$ and the carrier frequency ω_L, the CEP φ_L is a third important parameter to fully characterize the pulse. Therefore, its measurement and control are crucially impor-

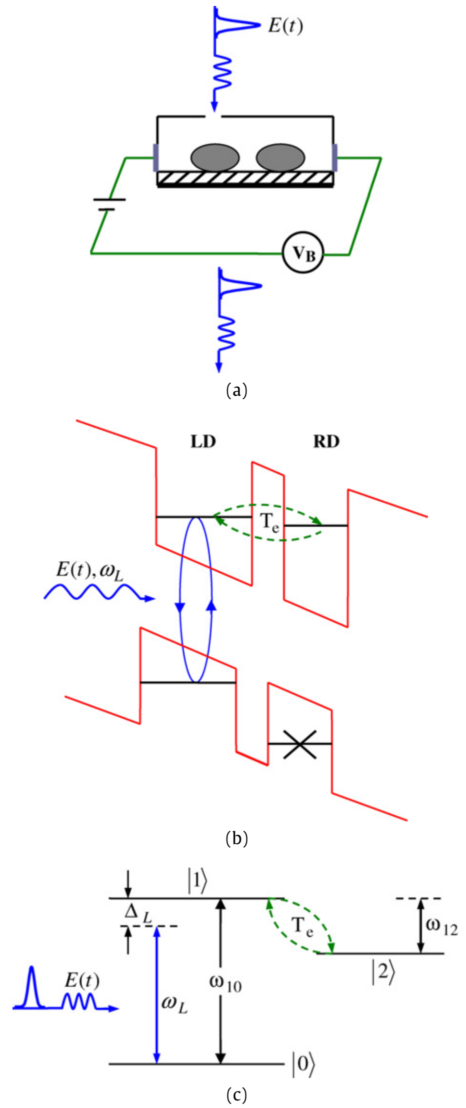

Fig. 1. (Color online.) (a) Schematic of the lateral geometry. Such lateral CQDs consisting of two dots (the left dot (LD) and the right dot (RD)) with different band structures coupled by tunneling. Samples are grown on GaAs(001) substrates by a unique combination of molecule beam epitaxy (MBE) and *in situ* atomic layer precise etching [27–29] which provides a low density homogeneous ensembles of CQDs consisting of two dots aligned along the [1$\bar{1}$0] direction. A few-cycle laser pulse transmits the left QD. V_B is a bias voltage. (b) Band diagram of CQDs. The red solid lines indicate the confinement potential in the $\hat{z}$ direction for electron (top) and holes (bottom). With an external voltage applied to a gate electrode, the conduction-band levels get closer to resonance, greatly increasing their coupling, while the valence-band levels get more off-resonance, resulting in effective decoupling of those levels. (c) Schematic of the energy level arrangement under study. A few-cycle laser pulse with carrier frequency ω_L and peak amplitude E_0 excites one electron from the valence to the conduction band in the LD, which can in turn tunnel to the RD. The ground state $|0\rangle$ is the system without excitations, and the exciton state $|1\rangle$ is a pair of electron and hole bound in the LD, and the indirect exciton state $|2\rangle$ is one hole in the LD with an electron in the RD.